COMPONENT PART NOTICE

THIS PAPER IS A COMPONENT PART OF THE FOLLOWING COMPILATION REPORT:

TITLE: Visual Effects in the High Performance Aircraft Cockpit.

TO ORDER THE COMPLETE COMPILATION REPORT, USE AD-A199 306.

THE COMPONENT PART IS PROVIDED HERE TO ALLOW USERS ACCESS TO INDIVIDUALLY AUTHORED SECTIONS OF PROCEEDING, ANNALS, SYMPOSIA, ETC. HOWEVER, THE COMPONENT SHOULD BE CONSIDERED WITHIN THE CONTEXT OF THE OVERALL COMPILATION REPORT AND NOT AS A STAND-ALONE TECHNICAL REPORT.

THE FOLLOWING COMPONENT PART NUMBERS COMPRISE THE COMPILATION REPORT:

AD#: P005 785 - P005 786 AD#: P005 787
AD#: P005 788 - P005 789 AD#: P005 790 - P005 791
AD#: P005 792 AD#:

DTIC FORM 463 MAR 85

OPI: DTIC-TID

AD-P005 790

NIGHT LIGHTING AND NIGHT VISION GOGGLE COMPATIBILITY

Alan R. Pinkus
Human Engineering Division
Armstrong Aerospace Medical Research Laboratory
Wright-Patterson Air Force Base Ohio 45433-6573
USA

SUMMARY

Proper lighting of aircraft instruments, panels, controls, indicators, and displays is essential in high performance aircraft. The lighting must be useable over a large range of ambient conditions; especially during dawn or dusk transitions and at night. It must be uniform, have low glare, and be continuously dimmable to very low luminance levels, so the pilot can become partially dark adapted for good, out-of-the-cockpit vision. Various aspects of cockpit lighting such as intensity levels, contrast, luminance and color uniformity, red versus white versus blue-green general lighting, color coding, and other parameters are discussed. Daytime lighting requirements will be noted throughout the paper because they are an important part of the overall design of the lighting system.

A special area of interest is night vision goggle compatible cockpit lighting. As night missions evolve, night vision goggles (NVGs) are being used with greater frequency. The characteristics and usage of NVGs are overviewed. Methods of achieving night vision goggle compatibility in the cockpit using filtered incandescent lamps, external bezels, floodlighting, light-emitting diodes, electroluminescent lamps, microlouver material, and black flight suits are described.

COCKPIT LIGHTING

Instruments, panels, switches, controls, indicators, and displays must be visible over a very large range of ambient lighting conditions. Ambient illumination ranges from 10^5 lux (10^4 foot candles) unobscured sunlight at altitude to a moonless, overcast night sky which is approximately 10^{-4} lux (10^{-5} foot candles). In the daytime, instruments and panels utilize the natural ambient light to be visible, whereas multifunction displays and annunciator signals must have high luminous output and good contrast to compete with the sun. Another demanding ambient condition occurs during dawn and dusk transitions. The cockpit can be in very dark shadows while the pilot is still viewing a very bright outside scene. The human eye can adapt to scenes that have about a 100 to 1 luminance range, while a dawn/dusk situation easily exceeds 1000 to 1. Depending on the sun angle, the pilot will turn the cockpit lighting to maximum, which is only 1 to 2 foot Lamberts (ft-L) for instruments and panels. Fortunately, this condition is of short duration. As the ambient illumination lowers, the pilot dims the cockpit lighting levels to reduce internal windscreen glare and increase his out-of-the-cockpit vision.

Dimming circuits are required to compensate for variations in the ambient illumination, different missions, individual pilot differences and preferences. Old style dimming circuits used discrete position switches that usually resulted in poor controllability. Continuously variable dimming is now used in most modern aircraft. Since the eye perceives logarithmic changes in luminance as near linear-like changes in subjective brightness, the dimming circuits should vary luminance logarithmically. To be effective throughout the entire ambient range, good controllability must be maintained from the 1 ft-L maximum through about 0.001 ft-L minimum before extinguishing (MIL-L-87240). Associated with dimming is tracking. As instrument and panel lighting is varied by the master control, individual units should appear close in brightness to each other. This is especially critical in the very low luminance range. For example, if an important instrument is dimmer than the others, a pilot will often turn up the master dimmer control until it is readable, but the rest of the instrument suite would then be brighter. Not only will this increase glare and internal reflections, but the entire cockpit also acts as an adaptive field to the eyes. The higher the adaptive field, the less sensitive the eyes will be to faint (near threshold) out-of-the-cockpit lights. It is for these reasons that the lower a cockpit can be uniformly dimmed, the better the external vision. To this end, some aircraft have individual dimmers, accessible by maintenance personnel, to balance out the lighting. When a new instrument or panel is installed, rebalancing may be required. Unfortunately, this balancing procedure is time consuming and has to be done at night by at least two people. Also, balancing requirements can reflect individual pilot visual differences or preferences in lighting, and aircraft are flown by different pilots on any given mission. Ideally, the individual trimmers would be accessible to the pilot, but the additional controls contribute to the complexity of the cockpit.

In an effort to verify cockpit lighting requirements, a field study was conducted by this laboratory at Eglin AFB, Florida. The study measured several qualities that related to night vision and lighting. Seven pilots served as subjects. Each pilot was dark adapted for at least 30 minutes. He then put on red goggles and was taken to either an F-15 or F-16 aircraft that was located at a dark, remote section of the

A-1 2.

field, away from lights. The pilot was seated in the aircraft, then instructed to remove his goggles and adjust the cockpit lighting to his normal nighttime settings. The windscreen was in the lowered position. The pilot then replaced his goggles and moved to a waiting area. Photometric equipment was then installed and luminance measurements of the pointers were taken on the airspeed, angle-of-attack, attitude direction indicator, horizontal situation indicator (HSI), altimeter, vertical velocity indicator, revolutions per minute (RPM), and temperature gauges. Mean instrument luminance readings (both aircraft) ranged from 0.04 to 0.023 ft-L. The lowest reading was 0.003 ft-L and the highest was 0.089 ft-L.

The tests were followed up by a questionnaire on cockpit lighting. All of the pilots felt the dimmers for these two aircraft had good controllability in the low end and the instruments could be dimmed as low as needed. Most pilots adjusted the main instruments to slightly higher levels than the side consoles. They preferred to read important main instruments, but with other instruments (such as RPM), they looked at pointer position only and these were often set at lower levels. Variations in luminance among instruments (balance) caused higher than desired setting. For example, the HSI had a poorly illuminated tumbler readout. Due to its importance, the pilots turned up the master dimmer so they could read the numbers, which in turn caused higher luminances and increased windscreen reflections. Maximum obtainable luminance settings were judged adequate. They were used for pre- and post-flight checks and dawn/dusk transitions. The side console panels created the most glare and reflections. Pilots often used small amounts of floodlighting to even out the cockpit illumination. As indicated by the data, dark adapted pilots set their instruments very low, thus verifying the minimum luminance, uniformity, and controllability requirements set forth in MIL-L-87240.

Contrast is as important a requirement as luminance and dimming. Except for color coding, instrument and panel surfaces are matte black with white markings, which yields the highest contrast over a large range of viewing conditions. Contrast is usually defined in military specifications as the difference between the scale and background luminances, divided by the background luminance. A contrast of 12 is typical for white markings and pointers on black backgrounds. A contrast of five is recommended for white on gray. Higher contrasts can be obtained by varying paints or using filters. However, very high contrast at night is not recommended since it can induce a visual illusion termed the autokinetic effect. Bright light sources (especially point sources) that have very dark surrounds may appear to be floating or moving when in fact they are stationary. Early lighting systems had luminescent paint markings on a black background and were floodlighted with ultraviolet light. Besides causing eye strain and increasing the risk of cataracts, the instruments had extremely high contrast, which had the undesirable result of inducing the autokinetic effect.

Over the past 20 years, cockpit lighting colors have changed from red, to white, and now most recently, blue-green for night vision goggle compatibility. Red was used to help maintain the pilot's partial dark adaptation because, at that time, out-of-the-cockpit vision was very important. There were several disadvantages which included eye strain and focusing problems that caused fatigue over time. Color coding of maps and instruments was also limited. As the pilots' eyes began to be supplemented by radar and other sensors, white lighting began to be employed. The main advantages of using white-lighted instrumentation were lower eye fatigue, higher visual resolution, and more effective use of color coding. For modern fighter aircraft, the US Air Force uses white lighting. Night vision goggle compatible lighting is blue-green because the red and infrared components have been eliminated due to their interference with the goggles.

When the pilot is looking out of the cockpit at night, the instrument and panel luminances act as an adapting field. Different average adapting luminances cause corresponding threshold changes, or levels of partial dark adaptation, for detecting a faint stimulus like a distant aircraft light. The color of any given field luminance also affects the eye's level of dark adaptation. Smith and Goddard (1967) measured the effect of cockpit lighting color on dark adaptation. The 50 percent probability of detection thresholds and 90 percent confidence limits were calculated. For a given adaptive luminance field, the probabilities of detecting the presence of a 200 micro ft-L stimulus were approximately 0.935 for red, 0.54 for white, and 0.3 for green lighting. The difference between thresholds after exposure to a green adaptive field versus the red field was statistically significant. Green versus white and white versus red comparisons showed no statistically significant differences between detection thresholds. It should be noted that the experimental setup used a floodlighted instrumentation panel which resulted in a large illuminance of the retina that would not be found in an edge-lighted suite. Also, the difference between the pure red and green conditions are a worst-case condition not usually found in a regular, color-coded (mixed colors) cockpit. Both of these factors caused larger threshold differences than would be expected in a real cockpit. From an operational standpoint, it is unlikely that different colors cause a significant decrement in the pilot's ability to detect faint lights outside of the cockpit, especially when considering the variability among crew members' vision and the large amounts of light emitted from populated areas. Also, the broadband nature of white and blue-green lighting seems to contribute to the reduction of visual fatigue over long periods of use.

Another important factor to consider is the effect color has on visual resolution, which relates directly to the visibility of small details within the cockpit. Figure 1 shows the smallest resolvable grating (half cycle in arc minutes) as 0.55 for red,

0.476 for white, and 0.466 for green, which is an operationally non-significant difference. The crew members' ability to resolve the relatively large lettering, pointers, scales, etc., is not effected, though the appearance of color coded markings, flags, or maps may be changed when viewed under various colors. Fine detail in maps would be more visible under white and green illumination.

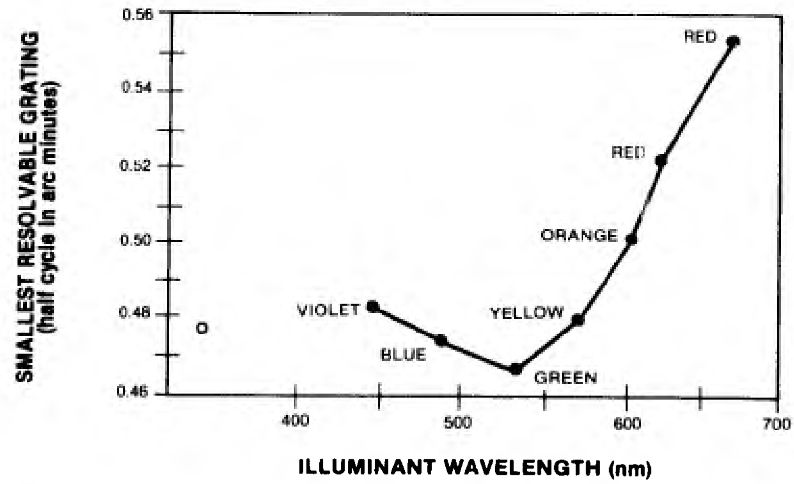

Figure 1. Visual acuity and illuminant wavelength.

The specification of color has undergone numerous changes. An early color matching scheme was devised by Munsell, which is still in use today. It consists of a large set of standardized color chips. Matching of a test sample to the chips was performed under the same illuminant. The drawbacks of this system were that matching varied from observer to observer and that it was a slow process to be performed routinely.

In 1931, the International Commission on Illumination, or Commission Internationale de l'Eclairage (CIE), devised a method to specify color matching that used the actual physical measurement of the spectral energy distribution (SED) curve instead of through subjective visual methods such as that used by the Munsell system. The SED curve is the relative energy output of a filtered or unfiltered light source plotted as a function of wavelength. The CIE system is based on the trivariance of vision, which is the physiological fact that any monochromatic light, is equivalent to the algebraic sum of suitable amounts of three reference lights or primaries. The actual chromaticity is determined by calculating the amounts of the three primaries required by a standard observer to obtain a visual match.

Figure 2 shows the spectral tristimulus values for the 1931 standard observer. Note that the $\bar{y}$ curve is the photopic curve, which is the subjective human visual response to light as a function of wavelength, or color. The $\bar{x}$ and $\bar{z}$ primaries do not physically exist, but were formulated to avoid negative colors.

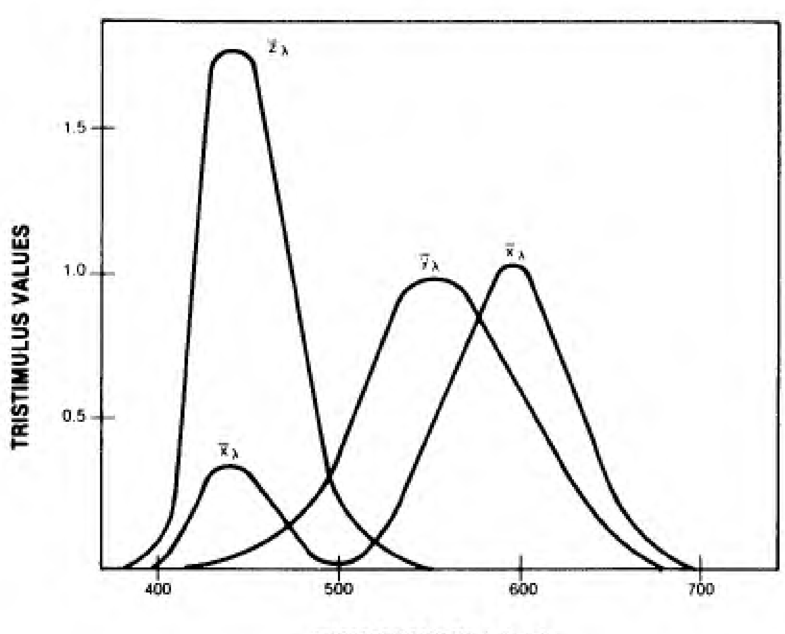

Figure 2. Spectral tristimulus values for the 1931 standard observer.

To calculate the CIE color coordinates, each tristimulus curve (Figure 2) is individually multiplied by the measured SED curve of the sample under consideration, and then integrated over wavelength, the resultant values of which are denoted by X, Y, and Z. Using these values, Equation 1 shows how the chromaticity coordinates x, y, and z are calculated. This procedure normalizes the chromaticity values so that x + y + z = 1.

$$x = \frac{X}{X + Y + Z}; \quad y = \frac{Y}{X + Y + Z}; \quad z = \frac{Z}{X + Y + Z} \qquad (1)$$

Figure 3 shows the 1931 CIE chromaticity diagram. There are several features that should be noted. Since the coordinates sum to one, typically, only the x and y values are plotted, the z value being determined by the others (two degrees of freedom). The upside down u-shaped part of the curve represents the 100% saturated, pure spectral colors, which are defined by a single wavelength, as labeled. This curved line is derived by taking the $\bar{x}$, $\bar{y}$, and $\bar{z}$ tristimulus values for each separate wavelength of the standard observer (Figure 2), and calculating the x, y, and z chromaticity coordinates using Equation 1, where $\bar{x}$, $\bar{y}$, and $\bar{z}$ are substituted for X, Y, and Z respectively. Another feature of the diagram is that the colors become pastel, or desaturate, toward the center until they are white. The 1931 CIE color space can only show if two colors match. Differences between two points are nonuniform with respect to human vision. Tolerances found about a point (e.g., the square box shown is x = 0.25 ± 0.05, y = 0.55 ± 0.05), such as those found in some military specifications, are misleading due to the nonuniformity of the 1931 color space.

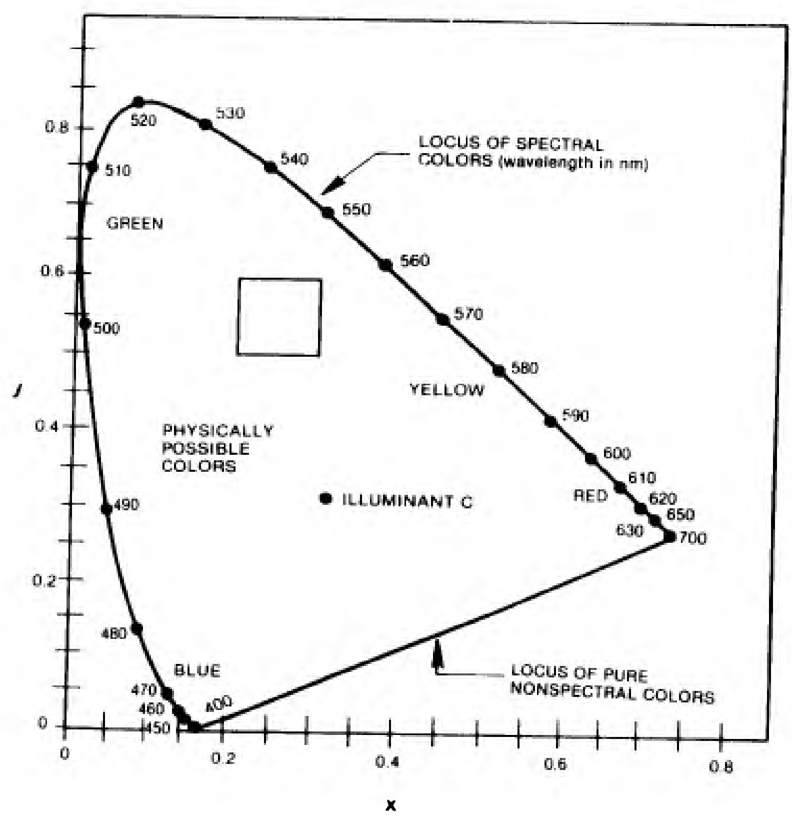

Figure 3. 1931 CIE chromaticity diagram.

The nonuniformity of the 1931 color space was investigated by MacAdam (1942). He measured the adjustment precision for color matching (made by one observer) at relatively high luminances. Figure 4 shows the results, the best fit of the data being ellipses. A common error when interpreting the data from this figure is that the axes of the ellipses are typically drawn ten times the size of the standard deviation of the actual data. MacAdam estimated that the minimum detectable chromaticity difference is three times the standard deviation. Note the nonuniformity among the different color regions.

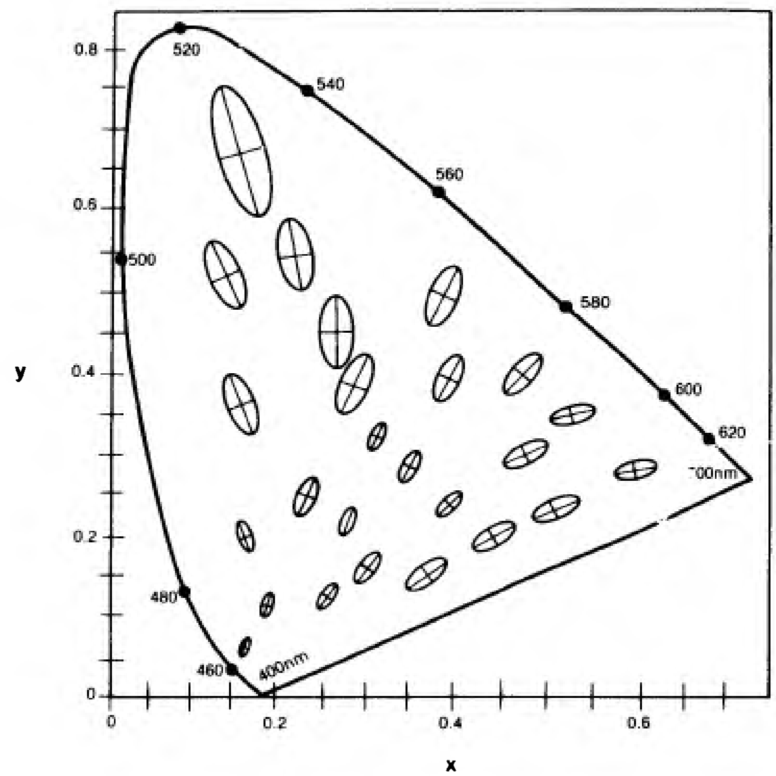

Figure 4. MacAdam's ellipses on 1931 CIE diagram.

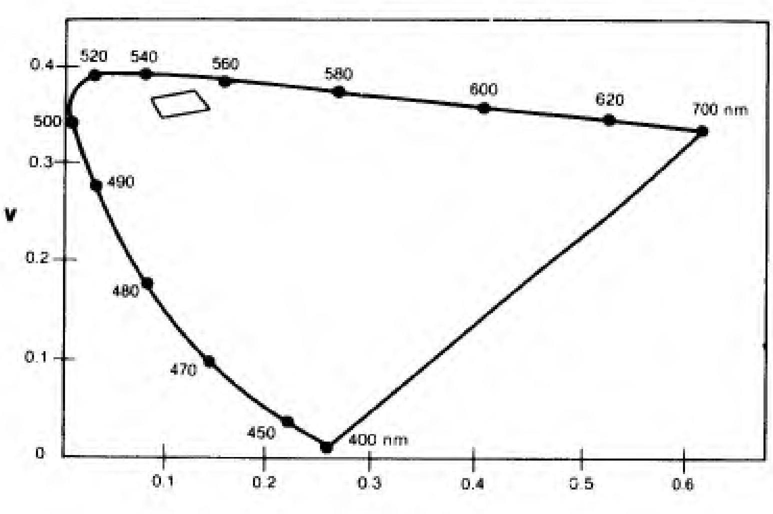

Figure 5. 1960 UCS diagram.

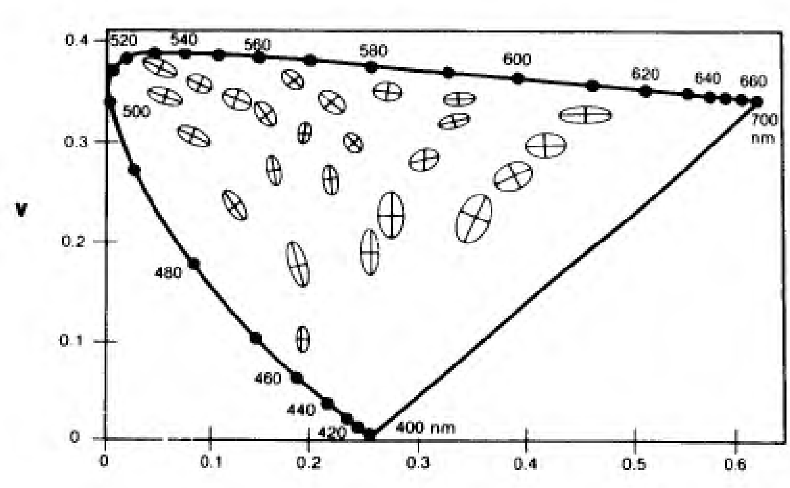

Figure 6. MacAdam's ellipses plotted on 1960 UCS diagram.

In 1960, the Uniform Chromaticity Spacing (UCS), as shown in Figure 5, was adopted in an attempt to make the color space more homogeneous with respect to human visual perception. The chromaticity coordinates were designated u and v. Note the square box from Figure 3 has been plotted on the UCS diagram and it now appears quite different. Figure 6 shows MacAdam's ellipses plotted on the UCS diagram, where again the ellipses are ten times the standard deviation of the actual data. It can be seen that, although it is nonuniform in some regions, it is very good in view of color sensitivity variations among individuals and is a good compromise between accuracy and simplicity. Tolerances about a point would be specified as either a circle or an amorphous area that would be empirically derived.

The mathematical relationship between the CIE and UCS color spaces is defined by Equation 2. The x and y CIE coordinates can be directly converted to u and v UCS coordinates. Modern color measurement equipment already performs these computations. Equation 3 shows how to convert u and v to x and y coordinates, respectively.

$$u = \frac{4x}{-2x + 12y + 3}; \quad v = \frac{6y}{-2x + 12y + 3} \tag{2}$$

$$x = \frac{3u}{2(u + 2 - 4v)}; \quad y = \frac{v}{u + 2 - 4v} \tag{3}$$

In 1976, the UCS diagram was further refined and designated CIE 1976 (u',v') UCS diagram, using u' and v' coordinates. It is shown in Figure 7 with the accompanying equations to convert from 1960 to 1976 space. The mathematical relationship between the 1976 and the 1960 spaces is u' = u and v' = 1.5v. Again, note the change of the tolerance box shape as replotted in the 1976 space.

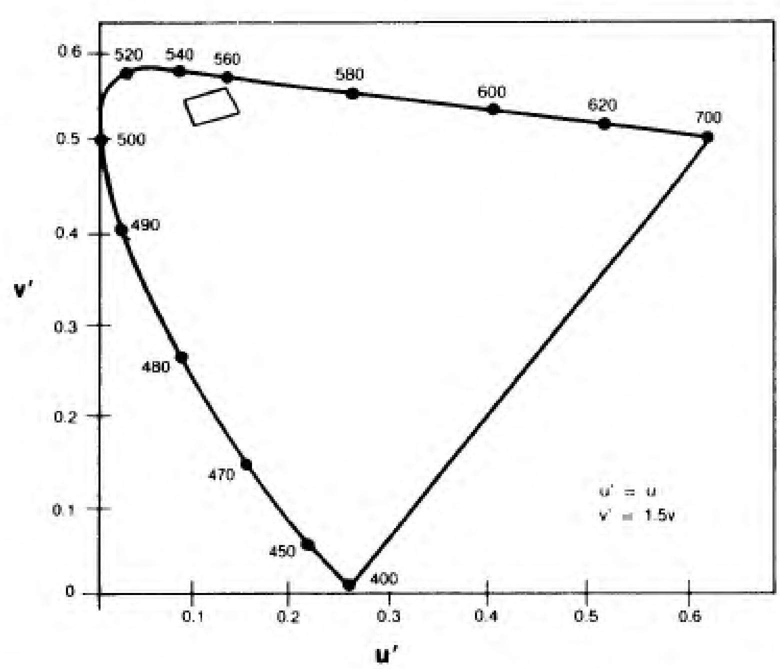

Figure 7. CIE 1976 (u',v') UCS diagram.

Given this background, practical applications using the CIE 1976 (u',v') UCS diagram can now be discussed in some detail. Figure 8 shows the 1931 CIE space with points of blue-green, green, and yellow-green light sources that represent candidates for night vision goggle compatible lighting applications. The distances among the points have little meaning due to the nonuniformity of the space and may be erroneously interpreted as having large perceived color differences. Figure 9 shows the same points plotted in 1976 space. Distances among points are now meaningful with respect to visual perception. The perceived color differences can be predicted to be small.

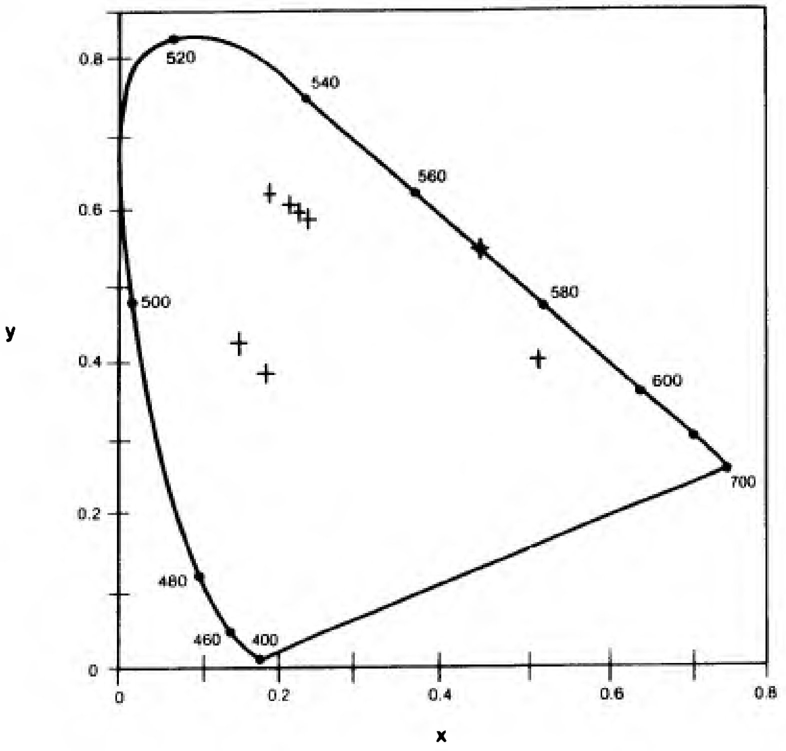

Figure 8. Various greenish colors plotted in CIE space.

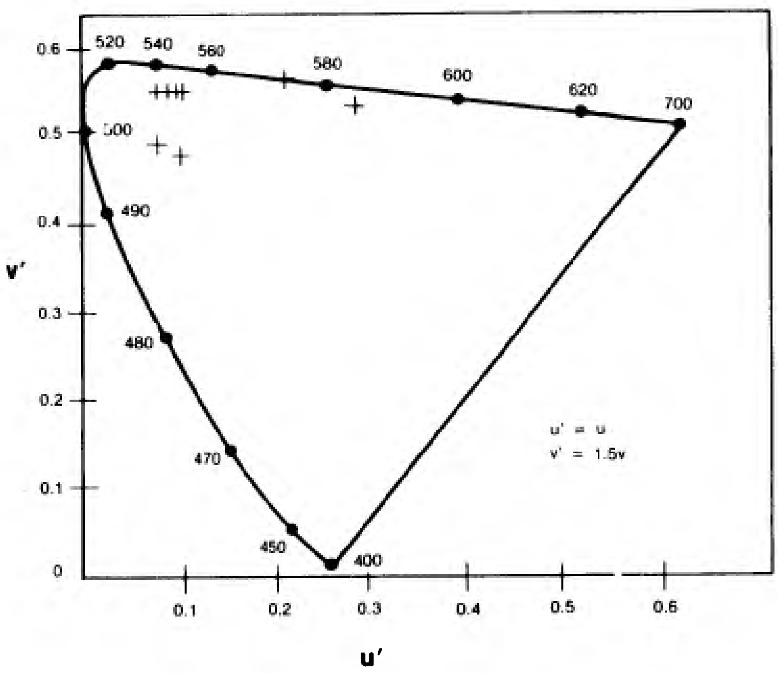

Figure 9. Same colors of Figure 8 replotted on the CIE 1976 (u',v') UCS diagram.

Color specification for aircraft should be defined in the 1976 space, not the 1931 space. The defined chromaticity areas should be based on performance criteria, not arbitrary tolerances or wholly aesthetic qualities. The limits should be empirically derived, if possible. For example, many specifications require one ft-L maximum luminance with chromaticity tolerances in 1931 CIE space. However, as was shown earlier, operational instrument luminances typically range from 0.1 to 0.001 ft-L. Figure 10 shows the perceived desaturation of hue (color) as a function of luminance (Hunt, 1953) in 1976 space. The outermost points (#1) are the actual measured chromaticity of variously colored lights at 314 ft-L. As the luminances of the lights were reduced

(points #2 through #5 were 19, 2.4, 0.8 and 0.09 ft-L, respectively), their perceived hue desaturated. While these colors appeared very different at the higher luminances, at operational levels they desaturated and appeared more similar. An additional factor is that many basic color experiments, such as the one constructed to derive the data in Figure 10, use standard and test color patches that are visually adjacent. Very small color differences are easily detected using this method. Lights in aircraft are usually separated by some small distance, which also makes the detection of the (perceived) desaturated light's color differences even more difficult. Given the low operational luminances and physically separated signals found in cockpits, some specified color tolerences may be too restrictive.

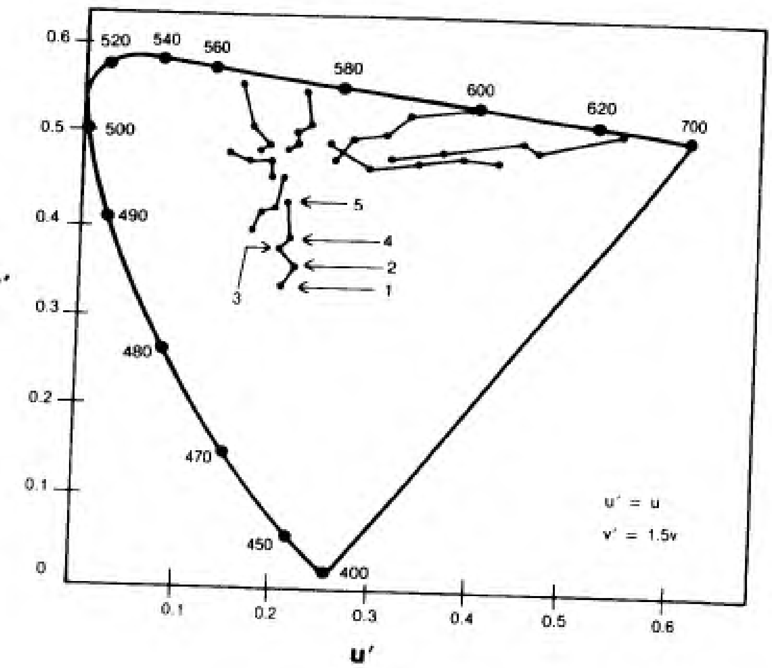

Figure 10. Perceived desaturation of hue as a function of luminance.

There are other performance criteria to be considered when specifying color tolerances. Variables that affect performance include: operational luminances, proximity of light signals, ambient lighting, chromaticity, and color coding. For empirical investigations, error rates, response times, fatigue, and workload may be used as evaluation criteria.

It has been shown that the 1931 CIE space is for matching colors only. The CIE 1976 (u',v') UCS diagram is more appropriate when specifying color tolerances. Color specifications and tolerances should be based on performance criteria, whenever possible.

Returning to other subsystem lighting requirements, illuminated pushbuttons have to be visible in high ambient illumination, as do warning, caution, and advisory signals. Several years ago, one hundred ft-L was common. Two to three hundred ft-L are required to be clearly visible. These signal lights are typically dimmed to 15±5 ft-L, which is still quite bright in a darkened cockpit. At night, the F-15 maintains the master warning and master caution lights at about 10 ft-L but employs continuous dimming for all other annunciator lights, down to an absolute minimum of 0.05 ft-L. The annunciator lights cannot be dimmed to extinction. Pilots report that this system works very well at night, especially when some of the signals (e.g., landing gear down) remain lit for relatively long periods of time.

Floodlights are used for pre- and post-flight checks, as an emergency backup system in case of a primary lighting system failure, as supplemental or fill lighting to the primary lighting, and during lightning storms to diminish the deleterious visual effects of the bright flashes of light. Aircraft that may be exposed to nuclear flashes have the floodlight system coupled to the automatic thermal protective closure systems for anti-dazzle. The highest floodlight illumination on the main instrument panel should be at least 100 ft candles and 150 ft candles for nuclear flashblindness protected pilots. The higher illumination is needed because, even though the protective closure system (PLZT) has been activated, it is not instantaneous and the pilot may still be exposed to a very bright flash. The higher cockpit illumination is needed to maintain instrument readability. Floodlighting must be continuously dimmable to very low levels before extinguishing. They must also have good, uniform coverage of the entire suite with a minimization of direct or reflected windscreen glare and few shadows on or within the instruments.

Head-up displays (HUDs) are specialized pieces of equipment, designed for specific aircraft and missions. To that extent, only the F-16 A/B and C/D HUDs will be overviewed. The F-16 A/B HUD has a total field of view (FOV) of 20 degrees. The stroke-written images must be visible against a background illumination of 10,000 ft candles

and have an average luminance of the symbol lines of 1,600 ft-L minimum. Contrast ratio is a minimum of 1.2:1 which is a 0.2 contrast. Note that achievable contrast for this display is much lower than that of painted instruments. Dimming is controlled by the cathode-ray tube (CRT) brightness control which is continuously variable. The control of the luminance is logarithmic so the subjective impression of the brightness changes is linear. A broad range of luminances is achieved by the insertion of a night filter into the optical path of the HUD. The CRT utilizes a green P-1 phosphor.

The F-16 C/D HUD differs from the A/B in that it has 25 degrees FOV, and it can display a raster generated image, like a television, with simultaneously displayed stroke-written symbology. The raster mode is used to display sensor imagery such as forward-looking infrared. The luminance and contrast for the stroke-written symbology is the same as the A/B HUD. In the raster mode, the HUD is capable of six shades of gray against a 30 ft-L background. Since this HUD has a raster capability, its night brightness mode is more difficult to achieve. It must be able to clearly and uniformly display information while not obscuring outside vision of a dimly lit scene such as a horizon lighted only by moonlight. The veiling, blank areas of the raster, cannot exceed 0.02 ft-L. This HUD also uses a green P-1 phosphor.

The F-16 C/D also utilizes a CRT multifunction display (MFD) that can display both 525 and 875 line vertical resolution. It is capable of 3,000 ft-L output, but is attenuated to 1,000 ft-L by the contrast enhancement filter. Brightness and contrast compensation are automatically changed as a function of ambient illumination down to 15 ft candles. The unit also has manual brightness and contrast controls that provide the pilot additional control over the display. Symbology brightness has a separate, continuous control. The F-16 A/B uses a radar/electro-optical CRT display that has a similar image display capability as the MFD described above, with the exception that its peak output luminance is 2,000 ft-L. Both displays utilize a P-43 phosphor.

NIGHT VISION GOGGLE COMPATIBLE LIGHTING

To this point, general and specific cockpit lighting characteristics and requirements for high performance aircraft have been described. A special area within this subject is night vision goggle compatible (NVGC) lighting. Night vision goggles (NVGs) are being used with greater frequency for night missions. NVGs amplify near infrared (IR) energy in order to enable the pilot to see at night. However, the standard lighting in aircraft emits large amounts of IR which interferes with the proper functioning of the goggles. The remainder of this paper will describe the basic NVG, light source characteristics, lighting specification, and the methods that are used to achieve NVG compatibility in the cockpit.

NVGs are electro-optical devices that detect, amplify, and display on a small green phosphor screen, visible and near infrared energy from dimly illuminated nighttime scenes. They look like small binoculars and can be worn on the aviator's helmet. NVGs utilize an image intensifier tube. As shown in Figure 11, the image intensifier tube has three basic elements: a photocathode for conversion of photons to electrons, a microchannel plate for electron multiplication, and a phosphor coating for conversion of electron energy back to photons for viewing. The output window is a bundle of fiber optics constructed with a 180 degree twist to yield a right-side-up image for viewing. The goggles have a FOV of 40 degrees and their resolution, in terms of human visual acuity, is about 2 arcminutes or 20/40. NVGs have an automatic gain feature that adjusts the sensitivity of the goggles to minimize bloom or wash out of the image.

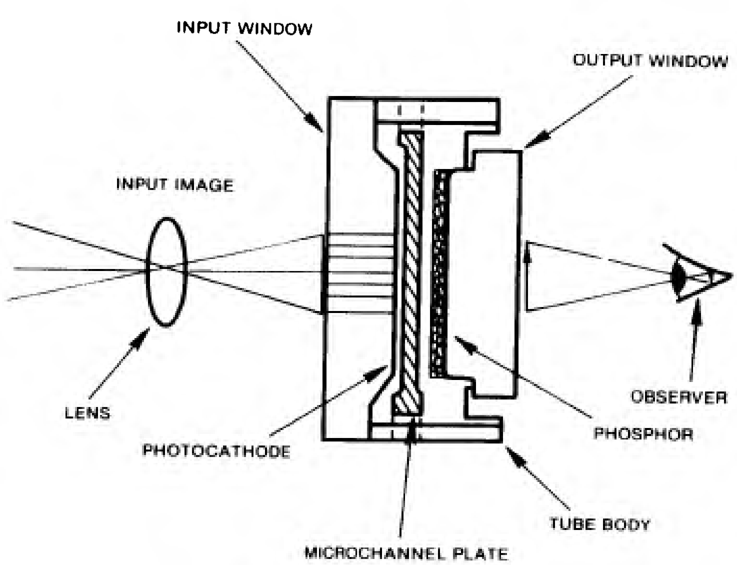

Figure 11. Image intensifier tube.

There are several types of NVGs currently in use (see Verona, AGARD-CP-379). They differ in their optics, spectral sensitivities, and packaging. The Army's original PVS-5 goggles were either strapped to the helmet or worn on the face, but peripheral vision was restricted. The PVS-5 goggles were then modified by cutting away the lower part for use in rotary and fixed-wing aircraft. It must be noted that aviators look through the goggles at outside scenes and underneath them, using direct, unaided vision (as represented by the photopic curve, Figure 12) to look at their instrumentation. The modified version is designated ANVIS-5 and both types used generation 2 image intensifier tubes, employing a multi-alkali photocathode. Another version with different optics and having greater sensitivity is designated generation 2-plus. Third generation intensifier tubes use a gallium arsenide photocathode, have even greater gain, and are more sensitive to IR energy as available from the night-sky spectral irradiance. Figure 12 shows the relative sensitivities of generation 2 and 3 NVGs, as a function of wavelength. Note the generation 3's greater sensitivity and shift toward the IR. The figure also shows the energy from the night-sky spectral irradiance, which is predominantly in the IR. Figure 12 also shows the spectral energy output of a standard white incandescent lamp. It can be seen that large amounts of energy are in the same region of the goggle's sensitivity. This IR pollution causes glare and reflects off the inside of the windscreen. The autogain adjusts to the higher input of the IR reflections, making it impossible to see the outside, lower energy scene.

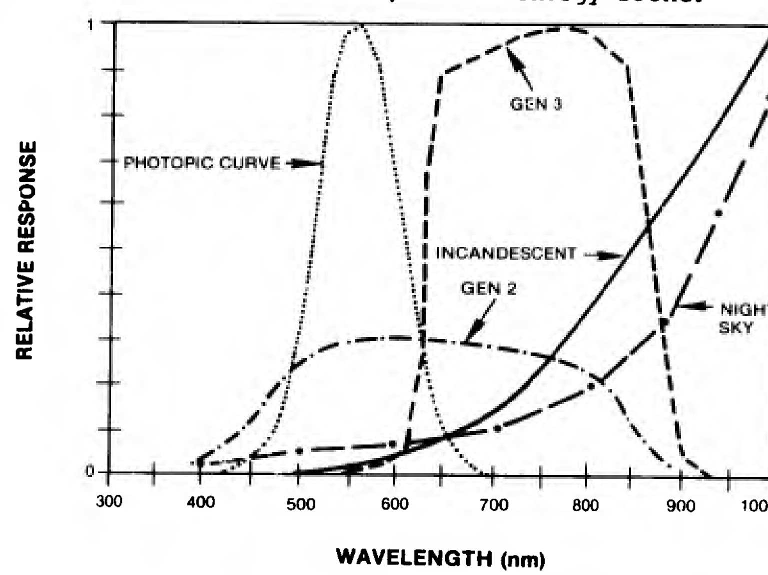

Figure 12. The photopic curve, generation 2 and 3 sensitivities, incandescent lamp curve, and night-sky spectral irradiance.

NVG compatibility is achieved by removing the IR energy from as many light sources as possible. It should be pointed out that, since generation 2 goggles use part of the visible spectrum as well as the IR, 100% NVG compatibility is difficult to achieve. However, filtering the IR energy from the lighting helps a great deal for generation 2 goggles. Filters are often placed on the goggles themselves, but performance is reduced. Generation 2 NVGs require extra filtering but generation 3 goggles have incorporated a minus-blue filter that blocks out visible light below 580 nanometers. Complete NVG compatibility is achieved with generation 3 goggles when the SED of the cockpit lighting does not overlap the goggle sensitivity. The cockpit lighting must still be visible to the unaided eye. The required luminance levels, as previously described, apply to a NVGC lighted cockpit. Removal of the red component of white light results in the characteristic blue-green colored NVGC cockpit. If the outside scene is bright, the NVGs will act as a relatively high (several ft-L) adaptive field, requiring slightly higher average instrument luminance settings by the pilot. A NVGC lighted cockpit, as seen through NVGs, has a greatly reduced IR signature from both inside and outside of the aircraft.

NVGC LIGHTING SPECIFICATION

The current military specification for NVGC lighting in aircraft is MIL-L-85762A. It is a comprehensive document that addresses lighting subsystems found within most aircraft. It has established the dimmed, nighttime luminance and illuminance levels at which an article is to be tested. Chromaticities for NVGC green, yellow, and red have been established in 1931 CIE color space. Measurement techniques and equations have been detailed to measure and calculate the luminances, illuminances, contrasts (with compensating multipliers), spectral energy distributions, and chromaticity coordinates of the lighting subsystems in question. The bottom line is that no cockpit light energy (for instrumentation at 0.1 ft-L) can exceed 1.7 X 10^{-10} watts/steradian-cm^2, which is the ANVIS-weighted radiance reflected by tree bark illuminated by starlight (see Breitmaier and Reetz, AGARD-CP-379). This value is believed to be the practical lower limit to conduct maneuvers and any cockpit lighting that exceeds this might cause interference with the goggles. It is a stringent criterion to meet and lights that are not in the goggle's FOV are penalized. Actual measurement of such low energy levels is also a practical problem, and requires specialized equipment.

Night vision goggle compatibility is defined as lighting that is sufficient for the unaided eye to read instruments and displays and, simultaneously, does not interfere with the operation of the NVGs in viewing scenes outside of the cockpit. Until

recently, there were no NVGC light specifications to use as guidelines for the manufacture of the needed lighting equipment. To this end, a framework and approach were developed by this laboratory (see Genco, AGARD-CP-379) to establish a more quantitative description of NVGC lighting. There are two broad areas of NVGC lighting that must be considered. The effects on direct, unaided vision and the effects on NVG performance.

The lighting effects on vision can be divided into four desirable attributes. (1) There must be sufficient light to read the instrumentation and displays. (2) It is preferred that color and intensity be relatively (perceptively) uniform. (3) If possible, retain color coding and cueing. (4) The lighting must be suitable for non-NVG night flights.

Item 1 is a hard requirement, since proper use of NVGs involves looking through the goggles to see outside and underneath them to directly view the instruments and displays. However, one should not immediately dismiss the possibility of eliminating (turning off) all lights to achieve NVG compatibility.

Item 2 is not a hard requirement, but is highly desirable. The easiest approach to specifying this characteristic is to designate an acceptable area of CIE color space. However, as stated earlier, CIE space is nonuniform with respect to visual sensation and color perception is greatly reduced for the lighting levels of concern for night operations. The first fact implies that the allowed coordinates, if expressed in 1931 CIE space, will not correspond to some symmetric geometric shapes (i.e., square or circle). As discussed earlier, it is more appropriate to specify a circular area in the CIE 1976 space since it relates more closely to human visual color discrimination. The second fact implies that the area in 1976 or 1931 space can be relatively large because it's just not possible to easily perceive color differences at these low light levels. The exact area in color space that is allowable is subject to discussion.

Item 3 is highly preferable, but again, not required. If the location and light level of indicator lights are carefully established, it is possible to retain the use of red and yellow light (limited uses) without affecting NVG operation. The present (1931 CIE) specification of these colors for cockpit use is probably acceptable.

Item 4 should probably be regarded as a hard requirement. It may be accomplished by providing auxiliary lighting for normal night flight which can be totally turned off for NVG flight.

The NVGs can be adversely affected in several ways: a NVG shutdown due to light sources in the field of view, severe contrast loss due to reflections of light sources in the windscreens, and loss of contrast due to flare (light scattering within objective lens of NVGs due to cockpit lighting). As a result of these effects, it is proposed that the lighting be considered in three categories. These three categories are divided according to the effect of the lighting on the NVGs. Category 1 is for lights that appear directly in the FOV of the NVG when viewing outside the cockpit. Category 2 is for light sources that are located so as to directly reflect in the windscreen. Category 3 is for light sources that are in the cockpit, generally adding to the IR pollution (neither Category 1 nor Category 2). To assess the level of compatibility of each of these light sources, it is necessary to calculate (or measure) the relative vision sensitive light compared to NVG sensitive light. This is done by calculating the compatibility ratio (C_R). The C_R is measured by calculating the ratio between vision sensitive light and NVG sensitive light as shown in Equations 4,5,6. Category 1, as depicted in Figure 13, is probably the most severe and will require the highest compatibility ratio. Category 2 (Figure 14) is also of considerable concern, but since the windscreen only reflects 8-10% of the light incident on it, the compatibility ratio for Category 2 sources may be somewhat less than Category 1. Category 3 (Figure 15) is the least severe since it represents general IR pollution in the cockpit. Note the yellow and red indicator lights should be situated so they fall into Category 3 in order to be NVG compatible.

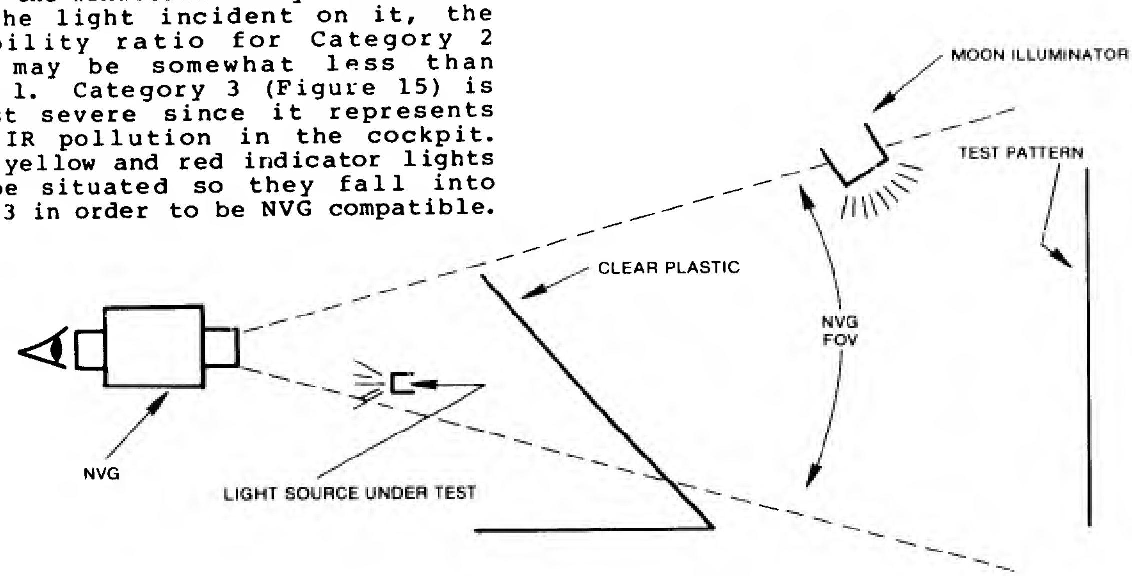

Figure 13. Category 1 lighting/goggle geometry.

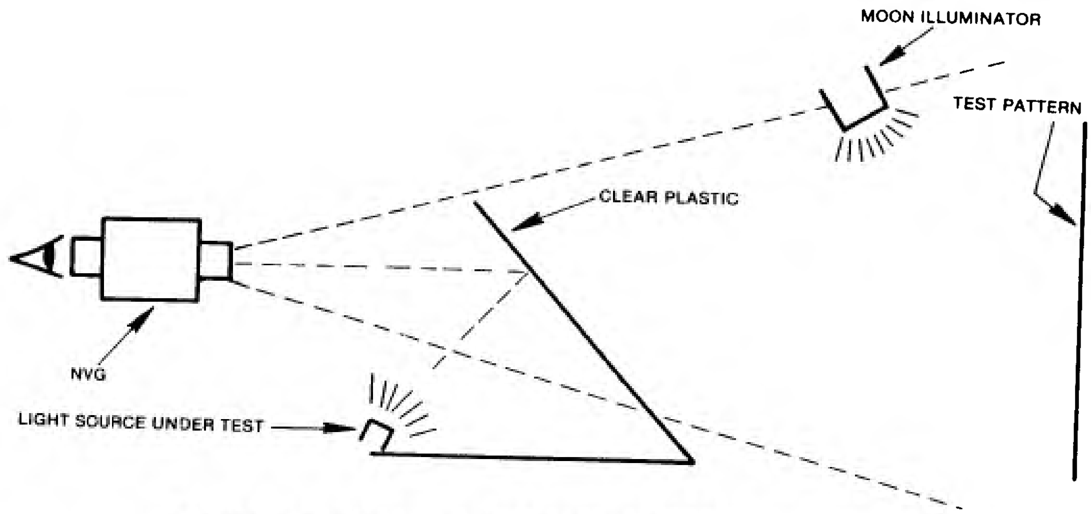

Figure 14. Category 2 lighting/goggle geometry.

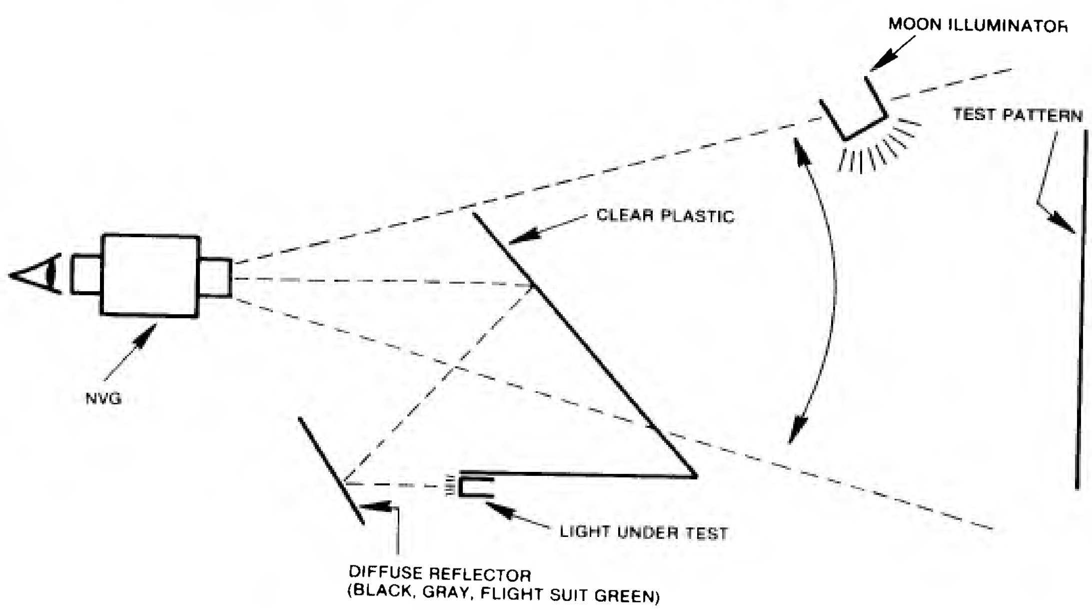

Figure 15. Category 3 lighting/goggle geometry.

Vision calculation:

$$\text{LUMINANCE} = L_V = 680 \int_{\lambda = 400\ \text{nm}}^{\lambda = 700\ \text{nm}} S(\lambda)F(\lambda)V(\lambda)d\lambda \qquad (4)$$

where: $S(\lambda)$ = Spectral distribution of light source (Watts/cm^2-STR-μm)

$F(\lambda)$ = Filter spectral transmissivity (no units)

$V(\lambda)$ = Visual spectral sensitivity (no units)

λ = wavelength

NVG calculation:

$$\text{RADIANCE} = R_{NVG} = K \int_{\lambda = 400\ \text{nm}}^{\lambda = 1000\ \text{nm}} S(\lambda)F(\lambda)G(\lambda)d\lambda \qquad (5)$$

where: $G(\lambda)$ = NVG spectral sensitivity
K = Proportionality constant (TBD)

Compatibility Ratio (C_R) calculation:

$$C_R = \frac{L_V}{R_{NVG}} \tag{6}$$

Equation 4 calculates the luminance the observer will see taking into consideration the spectral distribution of the light source, the filter's spectral transmissivity, the visual system's sensitivity, and integrating over the visible spectrum (400 to 700 nm). The calculated luminance value (L_V) forms the numerator in Equation 6. Equation 5 calculates the radiance amplified by the goggles by accounting for the spectral distribution of the light, the filter's spectral transmissivity, the goggle's sensitivity, and integrating over the visible and goggle spectrum (400 to 1000 nm). The calculated radiance (R_{NVG}) forms the denominator of Equation 6. The higher the compatibility ratio (C_R; Equation 6), the more stringent the requirement. Thus, Category 1 lights would have to meet or exceed a higher C_R than a Category 2 light. A Category 2, C_R would be higher than a Category 3, C_R.

The weighting of light sources according to their geometric relationship to the FOV of the NVGs and their subsequent effect on the compatibility, as calculated by the above equations, form a conceptual framework and predictive model for NVGC. Additional work is required to validate the model; however, the NVGC lighting specification (MIL-L-85762A) is currently undergoing revision that takes into account (through weighting) the geometric location of color CRTs.

NVGC LIGHTING TECHNIQUES

There are numerous methods that can be used to control the IR within the cockpit (see Task and Griffin, December 1982). Primary methods are light source selection and filtering techniques. Figure 16 shows the SED curves for unfiltered and filtered incandescent lamps, electroluminescent (EL) panels, and light-emitting diodes (LEDs) in relation to generation 3 NVG sensitivity. Incandescent lamps need to be filtered because of their high IR output. Incandescent lamps are blackbody radiators, thus their output varies as a function of temperature. EL is a cold light source that is essentially a capacitor with a CRT phosphor coating that glows when excited by an alternating electrical current. Figure 17 shows an exploded diagram of an EL lamp. As can be seen in Figure 16, green EL lamps emit very little, if any, IR energy. Certain LED colors also work well for these applications, as shown in the same figure.

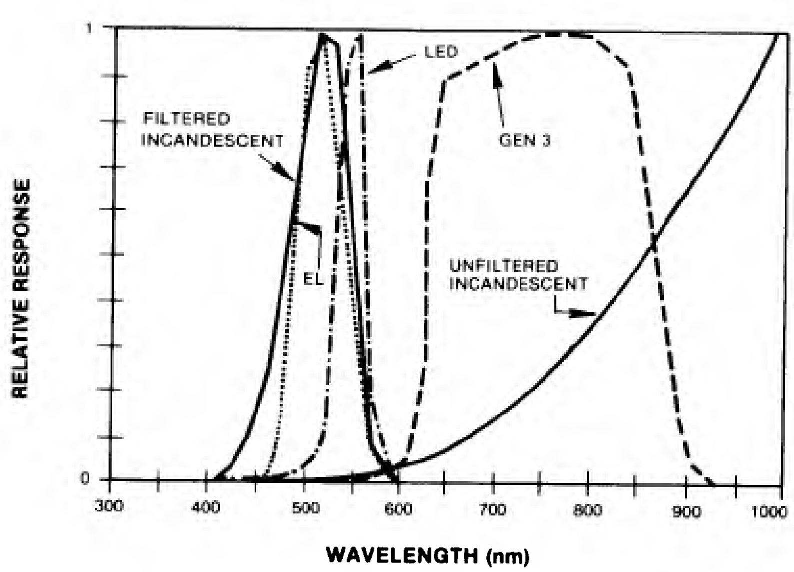

Figure 16. SED curves for unfiltered and filtered incandescent, EL, and LED light sources shown in relation to generation 3 NVG sensitivity.

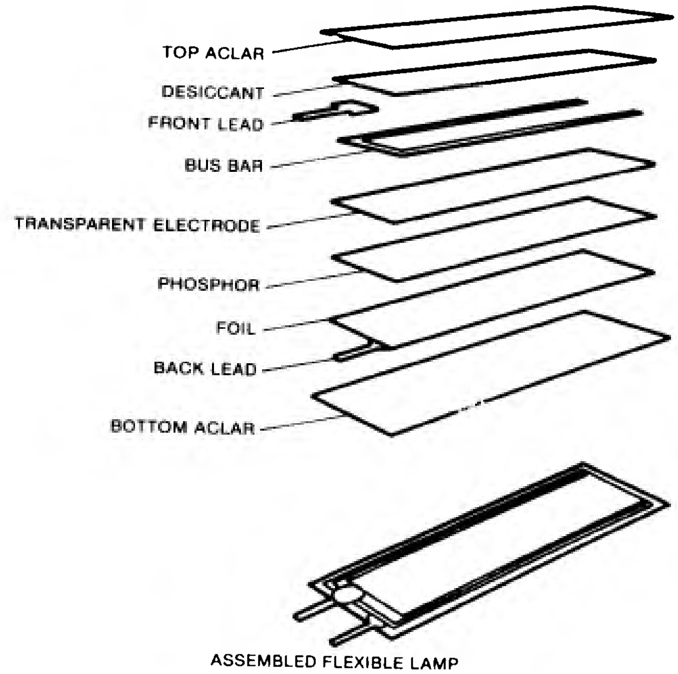

Figure 17. EL lamp construction.

In addition to source type and filtering, other methods are available to make a cockpit goggle compatible. Reflections on the inside of the windscreen can be controlled through the use of microlouver material, an extended glare shield, and black flight suits. Microlouver (ML) is a 1/16 inch plastic film developed by 3M Corporation that has numerous parallel baffles at a fixed angle, very similar to venetian blinds but very small and cast in plastic. By varying the baffle spacing and tilt, the fan of light that is allowed through the material can be controlled. ML comes in three fan widths of 48, 60, and 90 degrees and a specified tilt angle with respect to the vertical. Fan and tilt angles can be appropriately chosen to direct light from a display or light toward the pilot and away from the windscreen to reduce reflections. ML also reduces the amount of light, as well as resolution of detail, to the observer. While ML effectively controls visible light, it was found to be partially transparent to IR. An IR-blocking plastic film must be used over the display or light. With this modification, ML material can be successfully used in NVGC lighted cockpits.

Reflected glare can sometimes be controlled by extending the glare shield to reduce glow from the main instrument lights. The extension may also provide additional space to mount NVGC lights. A glare shield extension can be made adjustable, so different pilots can pull it in or out as needed. Care must be taken to not hamper the crew's escape pathways (through windows) or impinge on the ejection seat envelope of aircraft so equipped. Black, nomex flight suits are also desirable for use in NVGC cockpits to reduce reflections, as would a black helmet. Black suits appear to be more effective in partially modified cockpits where there is still some IR pollution being reflected. Fully modified cockpits have virtually no IR to be reflected, though external ambient energy could be reflected.

Aircraft can be modified to varying degrees of NVG compatibility, depending on the time and money available. A quick-fix modification is fast and low cost, but there is usually some reduction in visibility of the direct view instrumentation with some residual IR pollution. A full-up modification is costly and time consuming, however, it approximates state of the art NVGC lighting where there is essentially no IR and direct view visibility is excellent.

A quick-fix modification can be as simple as turning off the entire lighting system and illuminating the cockpit with filtered floodlights. Black tape can be used to cover indicator lights. Under the glare shield, incandescent lamps can be directly replaced with green LEDs. Various displays and lights can be fitted with Schott blue-green glass, Wamco glass, or Glendale green plastic filters that can be snapped on and off as needed. NVGC external light wedges, or bezels (see Figure 18), are sometimes mounted over the most important instruments.

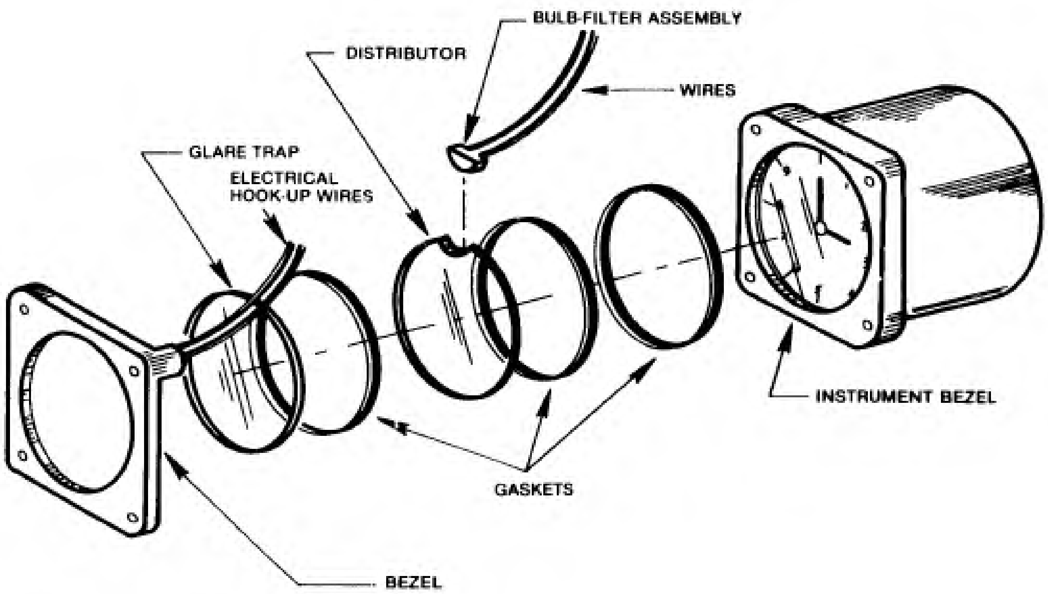

Figure 18. External light wedge (bezel) construction.

A full-up modification is very extensive. External light bezels (Figure 18) are placed over all instruments except the ones that are illuminated with small individual post (flood) lights. The post light caps are filtered. All floodlights and work lights are filtered. Green advisory and yellow caution annunciators are filtered to blue-green. Red warning lights are changed to NVGC yellow. All panels are replaced with NVGC green. Depending on the panel type, the light source is either filtered incandescent or electroluminescent. CRTs and moving map displays, if present, are covered with filters. Aircraft CRTs are often green P-43 phosphors that have a small red component that, if necessary, is easily filtered. Glass filters are best, due to their higher degree of stability under the extreme environmental conditions that are so often encountered.

CRTs used in radar, MFDs, and moving maps can be filtered to achieve NVG compatibility. HUDs usually have green, P-43 phosphor CRTs in order to obtain maximum brightness in the daytime. These types of HUDs can usually be turned down very low at night and directly viewed through the goggles. Focusing is no problem since the HUD is collimated, and the NVGs are focused at optical infinity to view the outside.

For aircraft that do not have HUDs, it is desirable to have flight information displayed while maintaining a head-up, out-of-the-cockpit position. This laboratory has developed a retrofit NVG/HUD system (see Genco, AGARD-CP-379) to perform this task. Figure 19 shows the NVG/HUD layout. The flight instrument raw signal information is collected by the aircraft's signal processing computer, converted into properly formatted data, and transmitted to the display unit. The display unit converts the data to symbols and displays them on a red CRT. Red is used so that the symbols are visible through the goggles. The symbology display is reflected from a front surface mirror to a relay lens which focuses the image onto a flexible fiber optic bundle. The bundle transmits the image to the NVG where a collimating lens projects the symbol image to optical infinity. This image is then reflected from a beam splitter into one ocular of the NVGs. The observer views the image of the HUD symbols superimposed over the outside view.

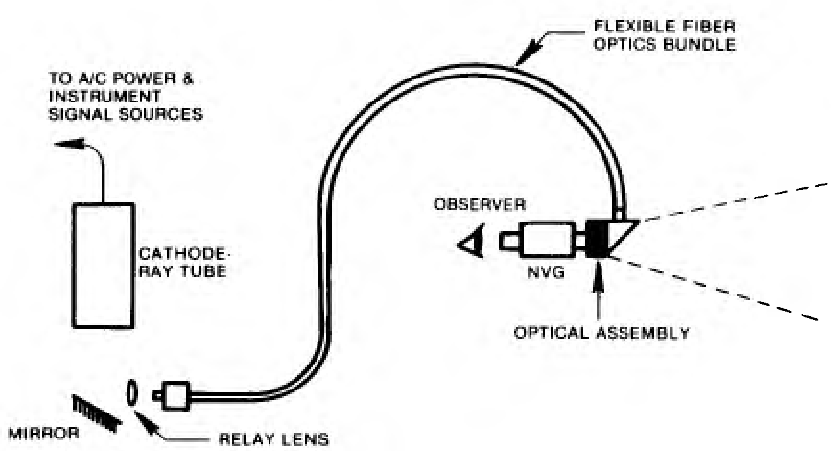

Figure 19. NVG/HUD Configuration.

This paper has described the night lighting requirements for high performance aircraft cockpits. It also overviewed NVG characteristics and defined NVG compatibility for cockpit lighting. Methods of achieving NVG compatibility were shown as represented by quick-fix and full-up modifications. These modifications greatly enhance the performance of NVGs that help the pilot to successfully complete his mission.

REFERENCES

Breitmaier, W.A. and Reetz, F., "Visual and spectroradiometric performance criteria for night vision goggle compatible aircraft interior lighting", from AGARD Conference Proceedings No. 379 entitled, "Visual Protection and Enhancement", Athens, Greece, 22-24 April 1985.

Genco, L.V., "Night vision support devices: human engineering integration", from AGARD Conference Proceedings No. 379 entitled, "Visual Protection and Enhancement", Athens, Greece, 22-24 April 1985.

Hunt, R.W.G., "The perception of color in one degree fields for different states of adaptation", <u>Journal of the Optical Society of America, 43</u>, (1953), pp 479-484.

MacAdam, D.L., "Visual sensitivities to color differences in daylight", <u>Journal of the Optical Society of America, 32</u>, (1942), pp 247-274.

MIL-L-87240 (USAF), Lighting Equipment, Airborne, Interior and Exterior, Military Specification, 16 December 1985.

MIL-L-85762A, Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible, Military Specification, 24 January 1986.

Smith, H.A. and Goddard, C., "Effects of cockpit lighting color on dark adaptation", AFFDL-TR-67-56, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, May 1967.

Task, H.L. and Griffin, L.L., "PAVE LOW III: Interior lighting reconfiguration for night lighting and night vision goggle compatibility", <u>Aviation, Space, and Environmental Medicine</u>, December 1982, pp 1162-1165.

Verona, R.W., "Image intensifiers: past and present", from AGARD Conference Proceedings No. 379 entitled, "Visual Protection and Enhancement", Athens, Greece, 22-24 April 1985.